# Simulations of SNAP Observations and Data Reduction

SNAP DOE Review, July 2002

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Scope of this presentation:
- How to go from instrument specifications and observing plan to cosmological constraints
- How do errors propagate through the process and requirements, optimizations flow down to the instrument & mission.
- What has been done and remains to be done.
- Results for nominal SNAP mission and alternatives.
- Weak lensing capabilities
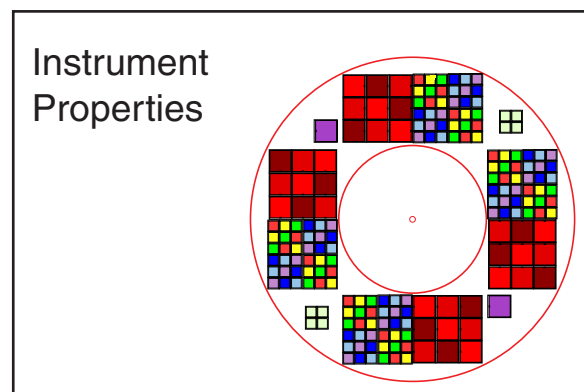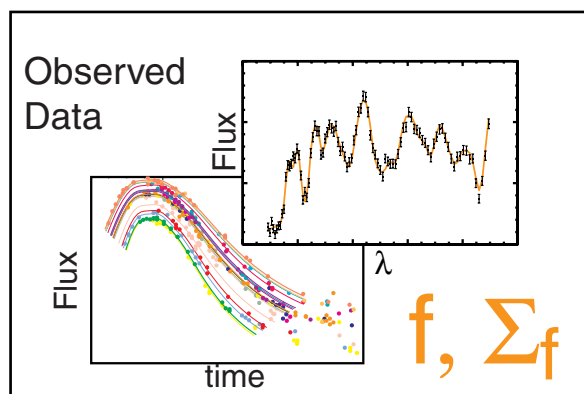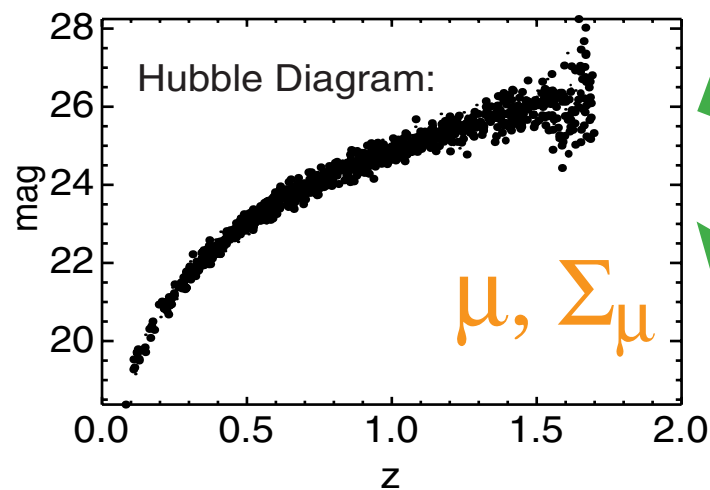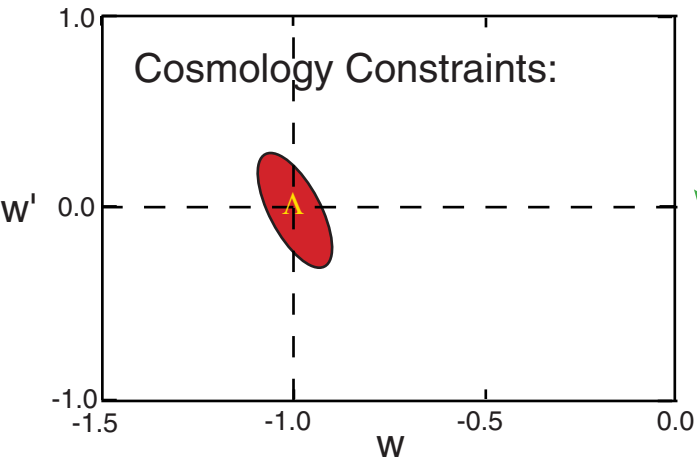
Data Flow:

Cosmology Constraints:

Hubble Diagram: μ, Σ_μ

External Cosmology Prior Constraints Σ_Ω

Observed Data f, Σ_f

External Supernova Observations Σ_{sn}

Calibration Program Constraints Σ_{cal}

Instrument Properties

Mission Plan

Requirements Flowdown

Science Goals:

- Determine Ω_m to 0.02, Ω_Λ to 0.04 for no prior, w=-1 (cross-check on CMB and other cosmology data)
- Determine w to 0.05, w' to 0.3, using strong priors on Ω_m and flatness expected from CMB.
- Aside from pure cosmological constant (w=-1), precise and well-motivated theoretical predictions are absent. Hence these top-level science goals are a bit "squishy."

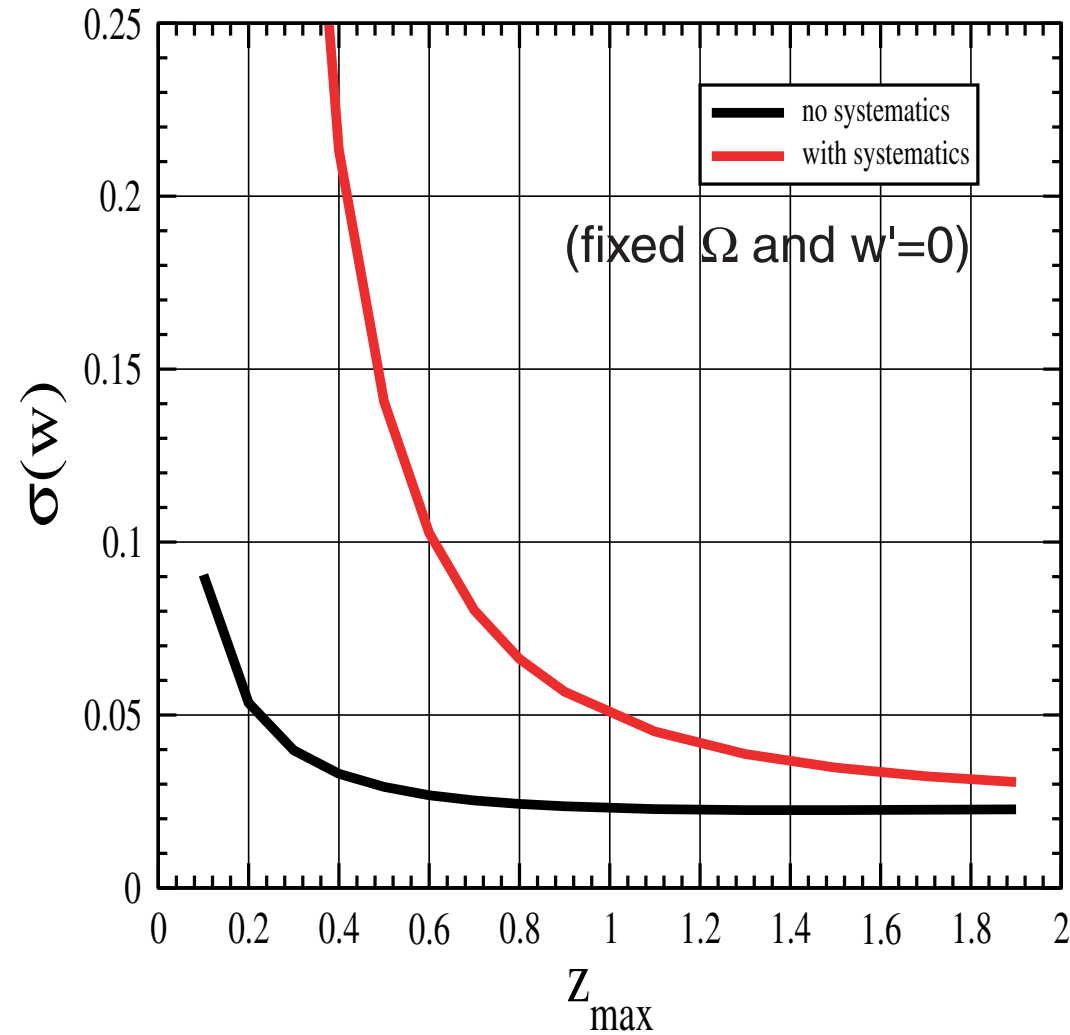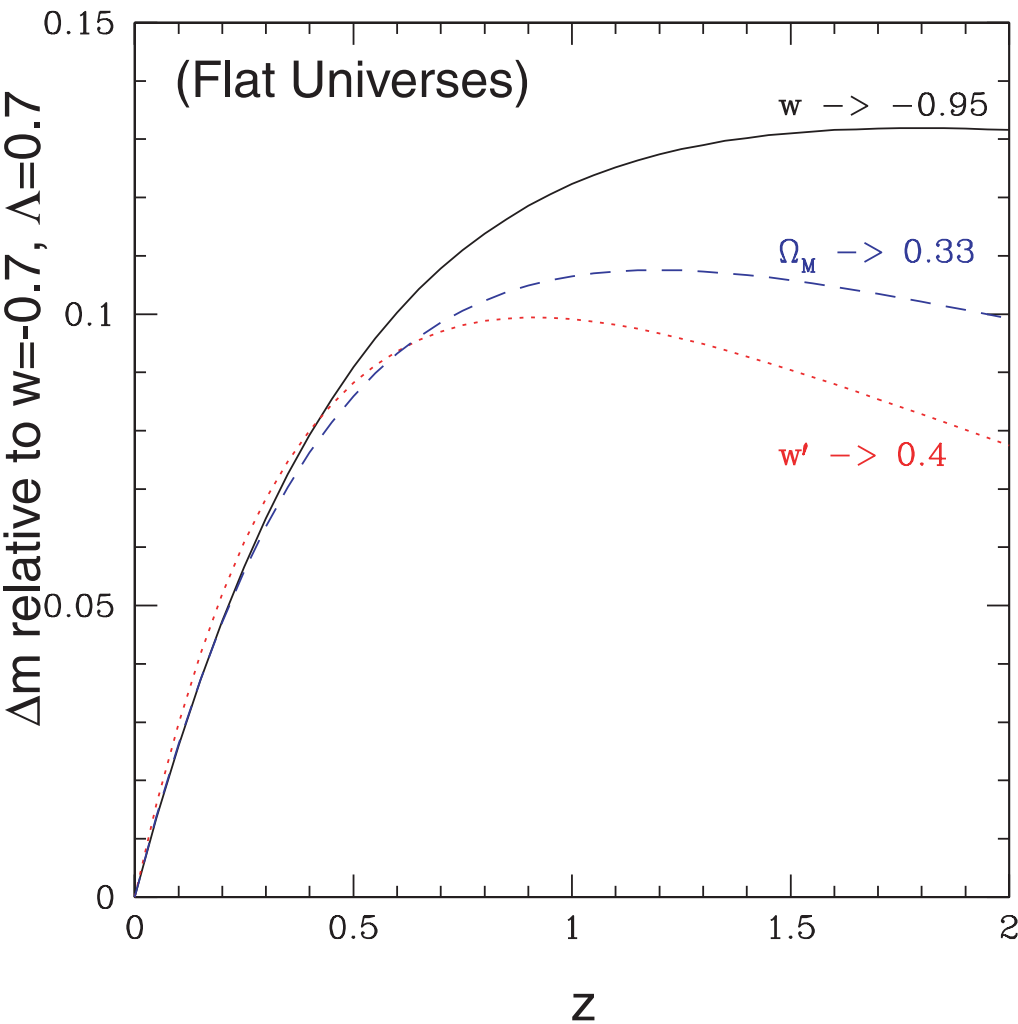Adapted from Weller & Albrecht (2000)
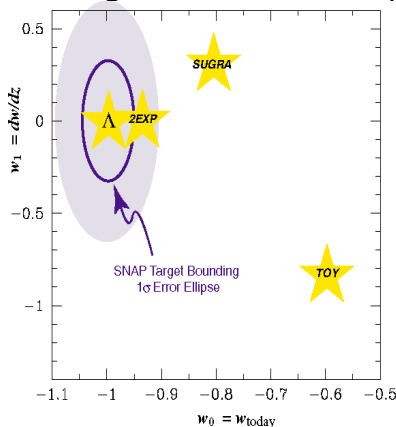
Cosmology Constraints from Hubble Diagram: (*cf*. E. Linder presentation)

- SNe data constrain cosmological parameters solely through the expected distance modulus $\mu(z)$. Predicted function is fit to observed vector μ of SN moduli **and the covariance matrix Σ_μ.**
- Two ways to test propagation of errors: direct fitting of simulated data, or Fisher-matrix analysis.
- Present Status: both direct-fit and Fisher methods have been successfully implemented and agree. Applied to simplified candidate Σ_μ matrices incorporating random SNe scatter plus calibration error model, grey dust, host dust.
- Future Work: Integrate cosmology fitter with upstream elements of simulation software for full exploration of observing schemes.

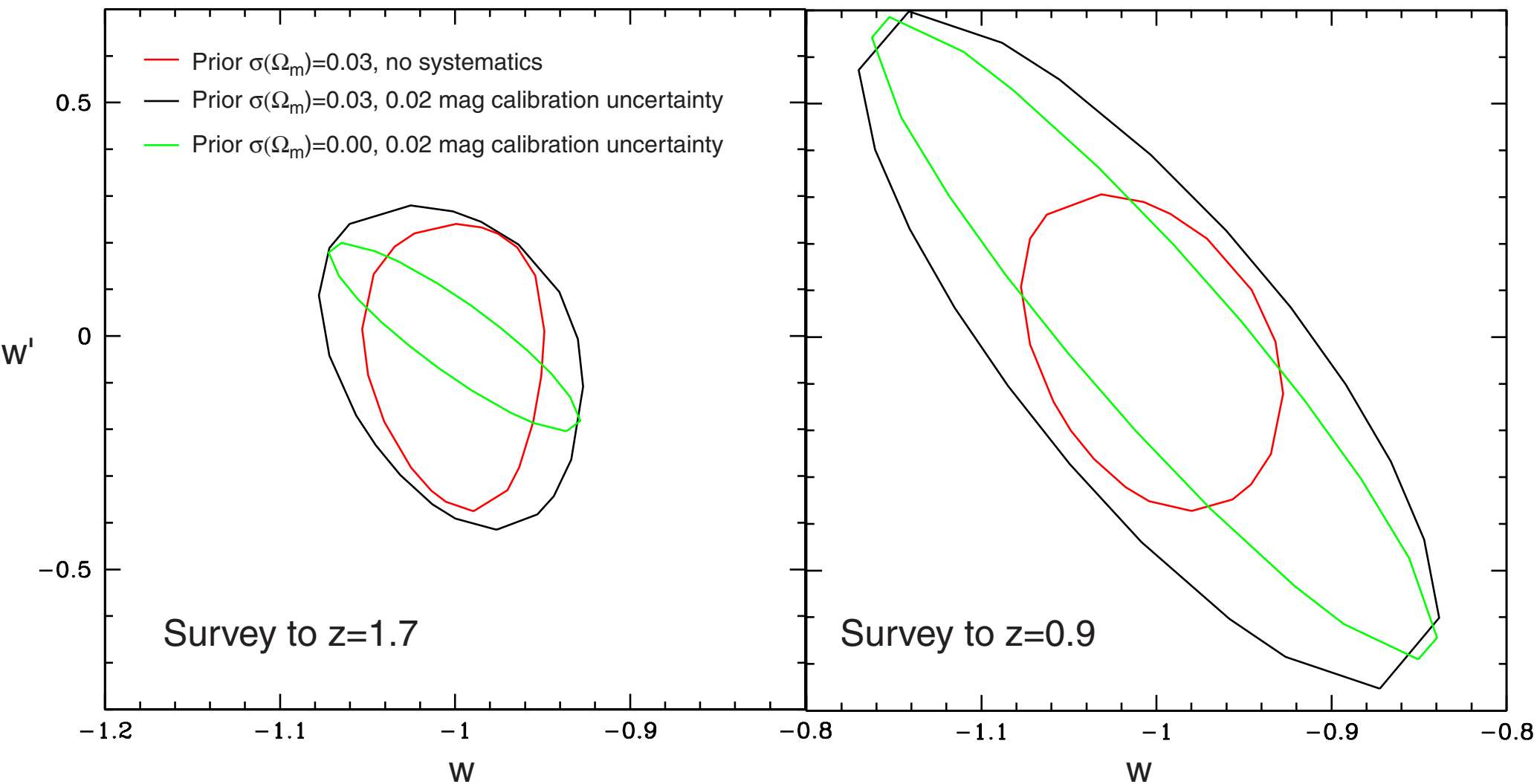# Cosmology Constraints from Hubble Diagram: Flowdown of Requirements

- No simple statement of requirements on Σ_μ because off-diagonal elements (correlations due to calibration errors) are critical. Most published estimates of survey accuracies have neglected these important effects that do not decrease as $1/\sqrt{N}$. Range of z also affects required Σ_μ.
- Survey to z>1 essential for reasonable systematic errors.

Different cosmologies cannot be distinguished solely with low-z data in the presence of 0.02 mag of photometric zeropoint variation:

(Flat Universes)

$w \to -0.95$

$\Omega_M \to 0.33$

$w' \to 0.4$

Δm relative to w=-0.7, Λ=0.7

z

$\sigma(w)$

(fixed Ω and w'=0)

no systematics
with systematics

z_{max}

(E. V. Linder & D. Huterer)

Effect of Limiting Redshift for Fixed Number of SNe

Prior σ(Ω$_m$)=0.03, no systematics
Prior σ(Ω$_m$)=0.03, 0.02 mag calibration uncertainty
Prior σ(Ω$_m$)=0.00, 0.02 mag calibration uncertainty

Survey to z=1.7

Survey to z=0.9

(E. Linder)

Photometric Accuracy from Instrument and Mission Specifications:

- Point-source photometry is a common astronomical problem.
- Estimate of S/N for given scenario must account for:
    - Diffraction and aberrations
    - Charge Diffusion
    - Pixel response function
    - Undersampling
    - Dithering
    - Host galaxy subtraction
    - Atmospheric Seeing & Extinction (ground only)
    - Poisson noise from source
    - Zodiacal Background
    - Dark Current
    - Read Noise
    - Flatfield Errors
    - Readout and pointing overheads.
    - Cosmic Rays

Those in red are not included in most exposure-time calculators. We have developed a methodology to incorporate ALL of these effects into an estimate of optimal point source extraction accuracy.

Photometric Accuracy from Instrument and Mission Specifications:

- Present Status:
    - o Software complete which accounts for all of above effects.
    - o Already used to optimize imager specifications.
    - o Integrated into Monte-Carlo pipeline.
- Future Work:
    - o Create simulated images to insure that host-galaxy subtraction is indeed nearly perfect.
    - o Algorithms for robust image combination, subtraction, cosmic-ray rejection, optimal photometry.
   - o Use to analyze larger set of alternative approaches

Photometric Accuracy from Instrument and Mission Specifications: Flowdown Results

- Note that photometric and spectroscopic speed can be optimized without doing end-to-end mission simulation. Current parameters of instruments have been set using results of photometric error analyses.
- Charge diffusion identified as a substantial efficiency loss in CCD design. Specification has been tightened as a result (3.5 microns from 5 microns), ~50% speed gain.
- Undersampled pixels shown to have little effect upon photometric and astrometric accuracy as long as 2x2 dithering scheme is used.
- Comparison with best existing ground-based survey technology shows huge SNAP advantage relative to ground.
- The SN-optimized camera design is also an optimum for weak lensing surveys!
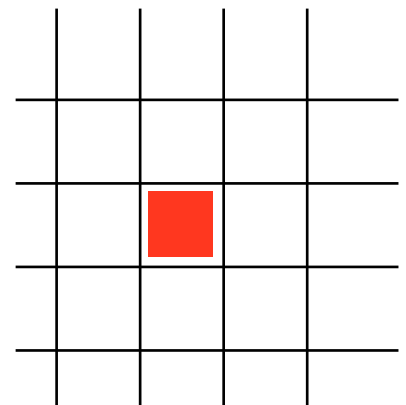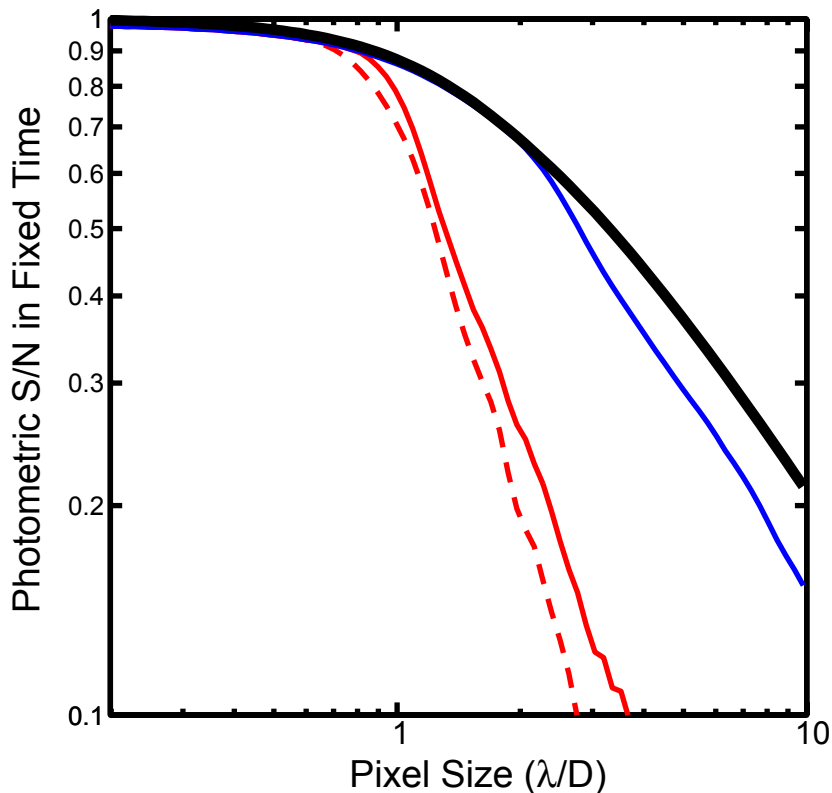- This portion of the simulation is very well understood.

Effect of CCD Charge Diffusion on Photometric Speed
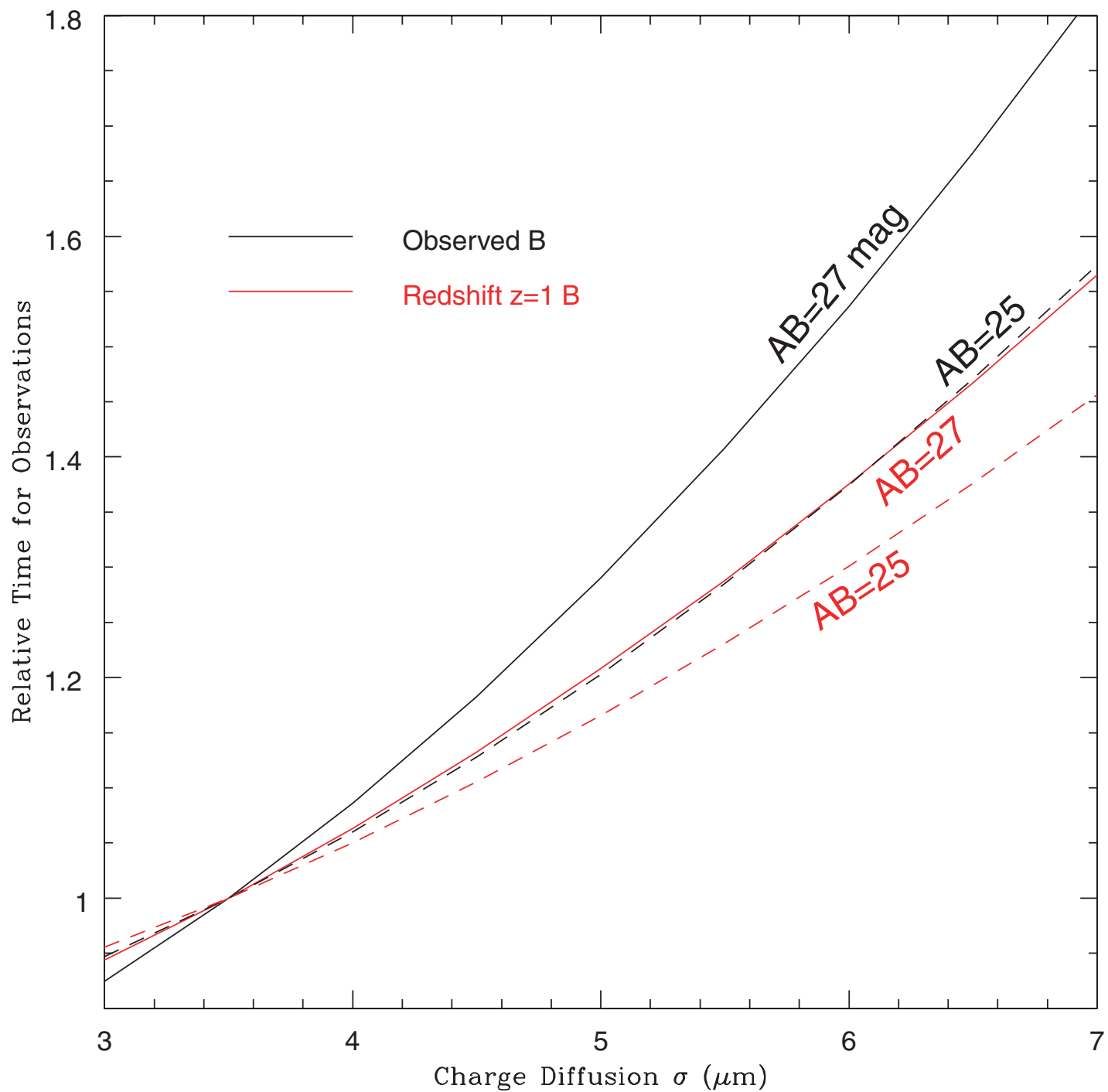
How Much Dithering is Best?
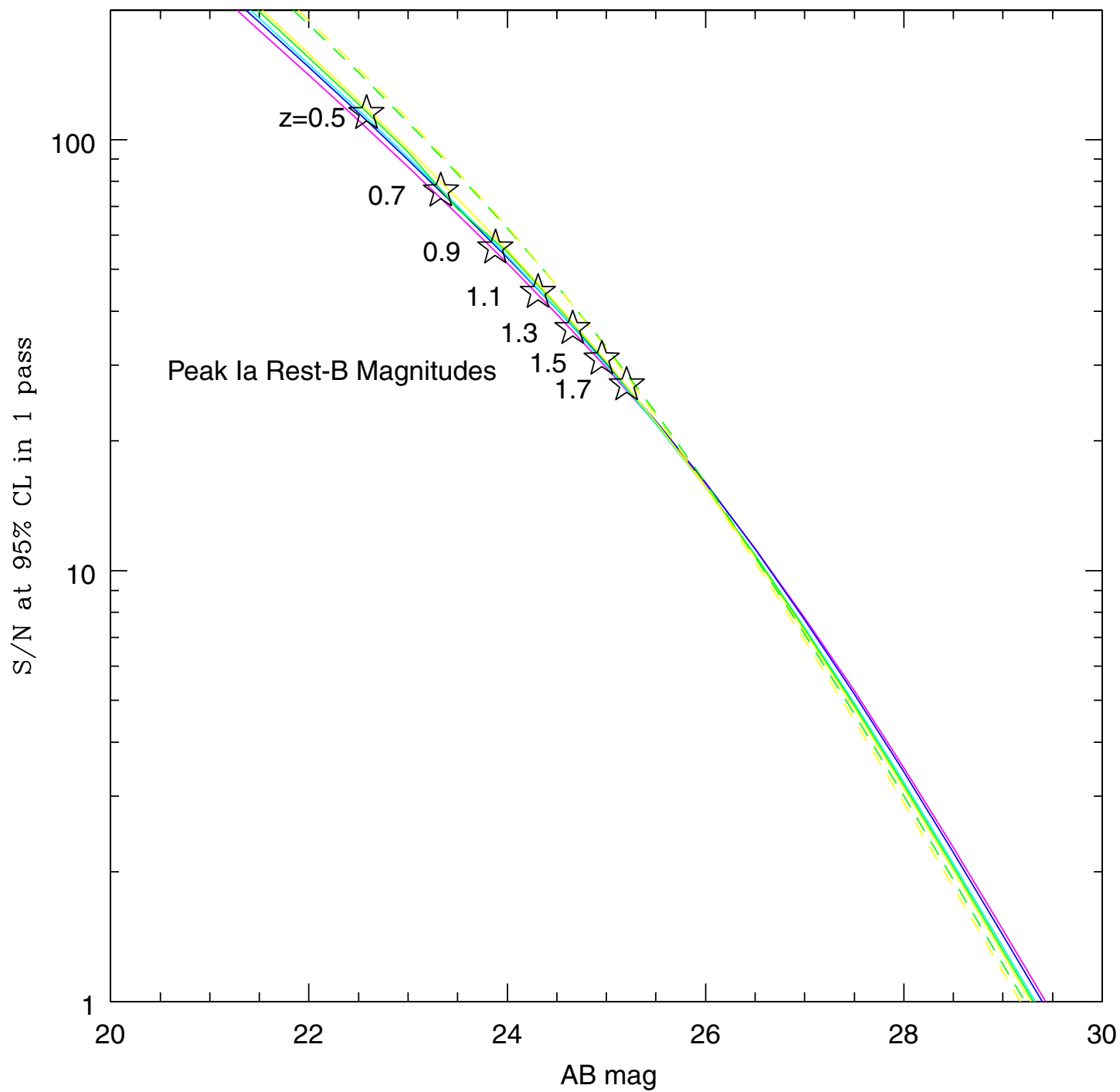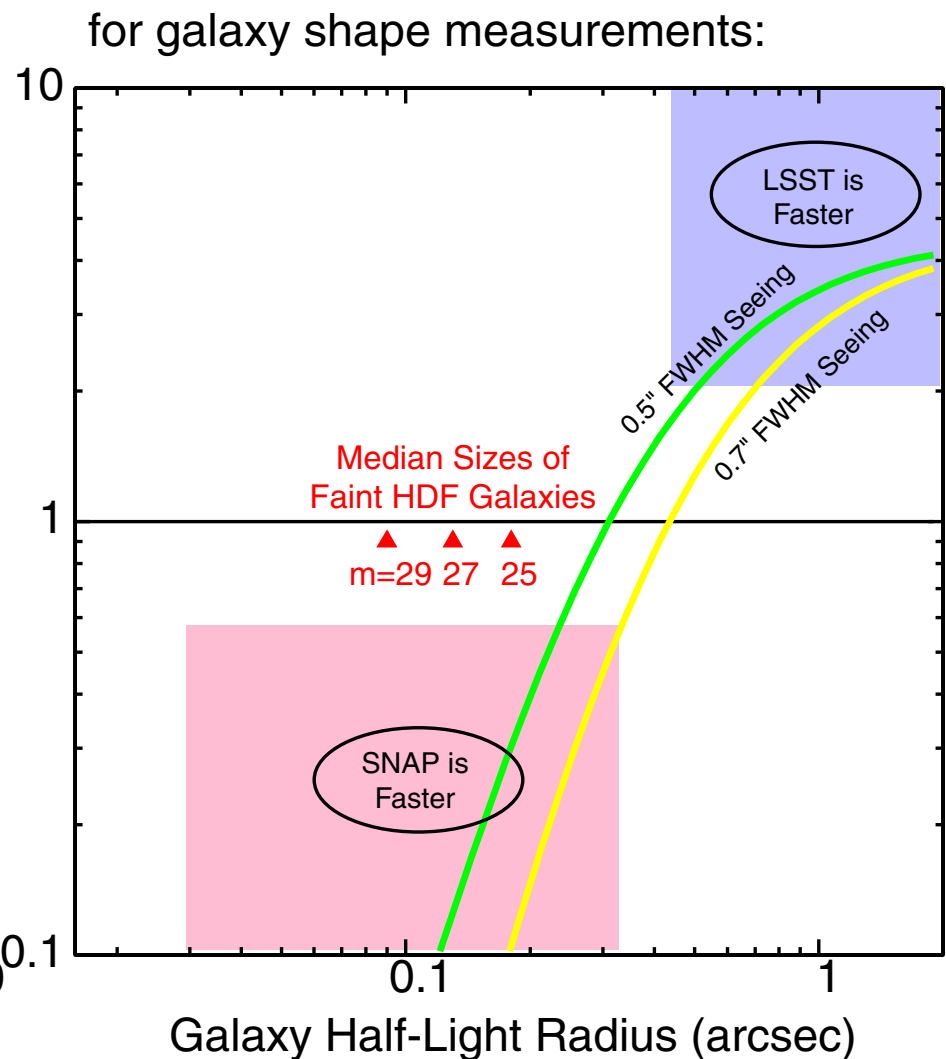## (for point-source photometry)
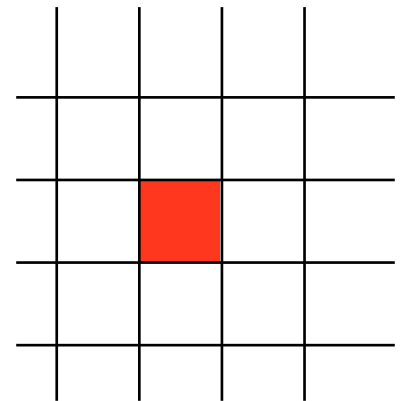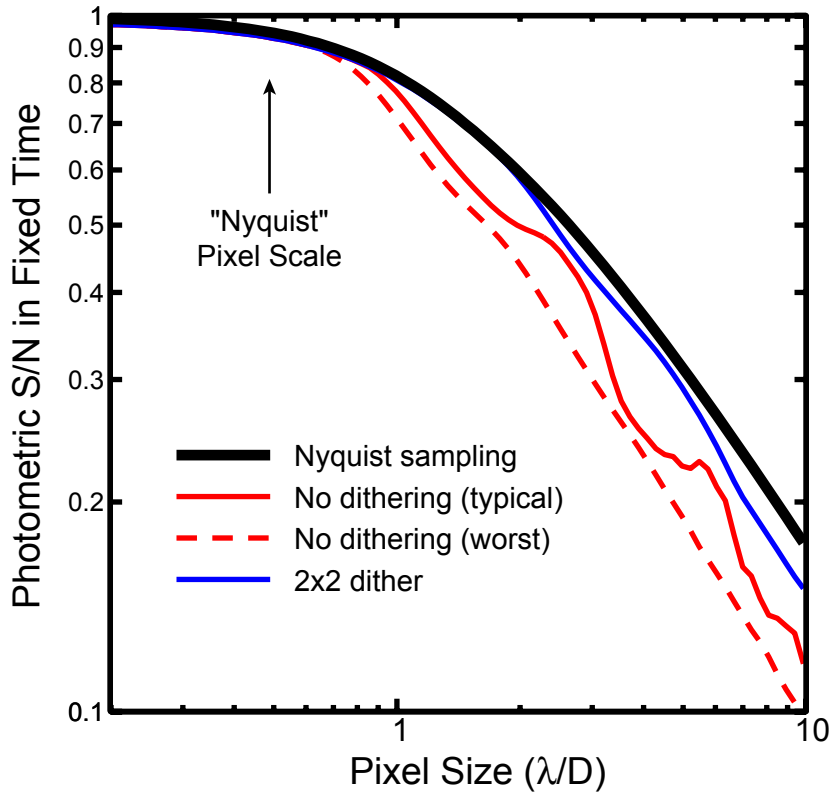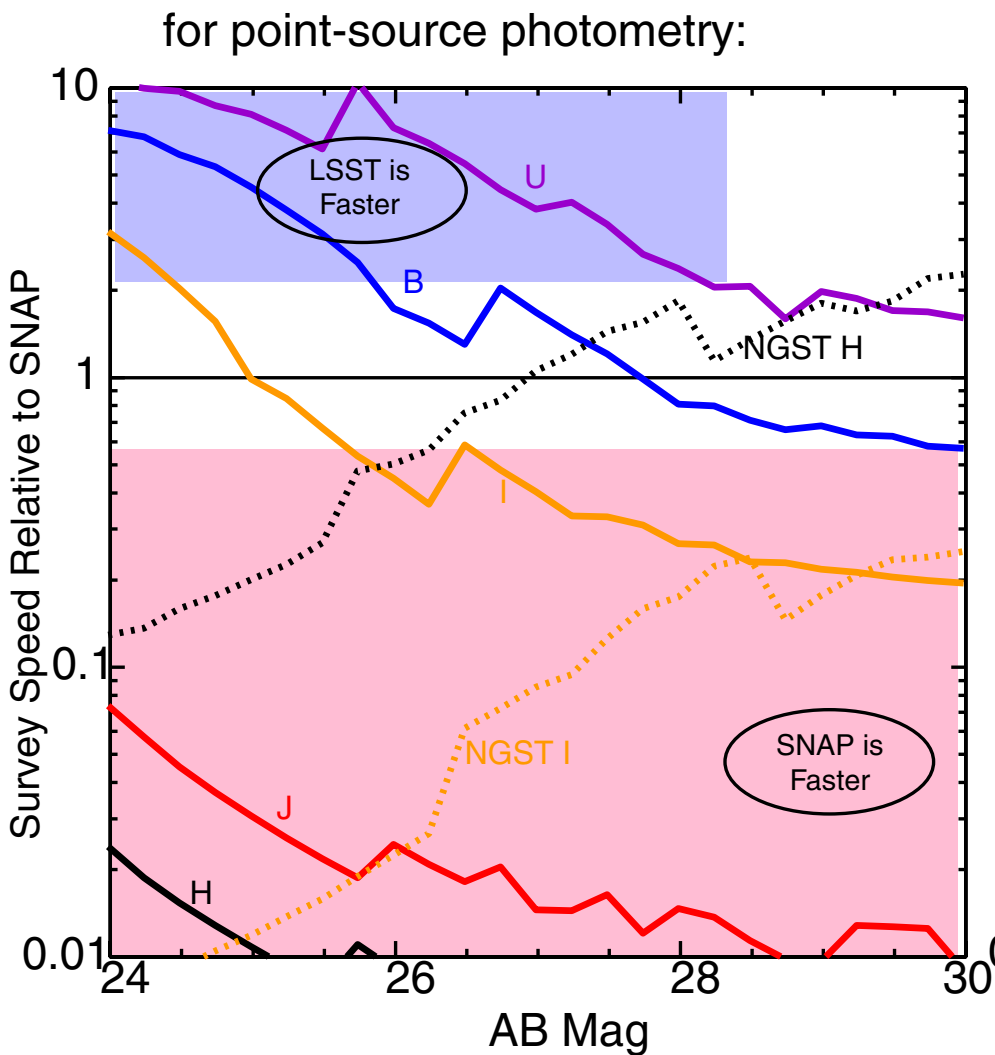

Perfect square pixel response

Pixel with 10% "dead zone" at edges

...2x2 dithering pattern recovers nearly all photometric information!

Point Source S/N for Nominal Single-Pass SNAP Observation

S/N at 95% CL in 1 pass

AB mag

z=0.5

0.7

0.9

1.1

1.3

1.5

1.7

Peak Ia Rest-B Magnitudes

Which is more effective: ground or space survey?

for point-source photometry:

for galaxy shape measurements:

LSST is Faster

LSST is Faster

SNAP is Faster

SNAP is Faster

U

B

NGST H

I

NGST I

J

H

Survey Speed Relative to SNAP

AB Mag

Median Sizes of Faint HDF Galaxies

m=29 27 25

0.5" FWHM Seeing

0.7" FWHM Seeing

Galaxy Half-Light Radius (arcsec)

NOTES: speeds here assume entire array is devoted to a single filter. Changes in SNAP and LSST specifications may result in up to factor 2 changes.

Spectroscopic Accuracy from Instrument and Mission Specifications:

- Photometric S/N programs also give S/N per spectral sample because image slicer produces a series of narrow-band images. Hence S/N estimates given resolution and sampling are well understood.
- Purpose of spectroscopy is to measure features too narrow for filter bands. These features are indicative of intrinsic properties of the supernova.
- Given S/N per resolution element and derivatives of spectrum w.r.t. SN physical properties, Fisher matrices give uncertainties on these parameters. Most difficult to measure: metallicity (log Z).
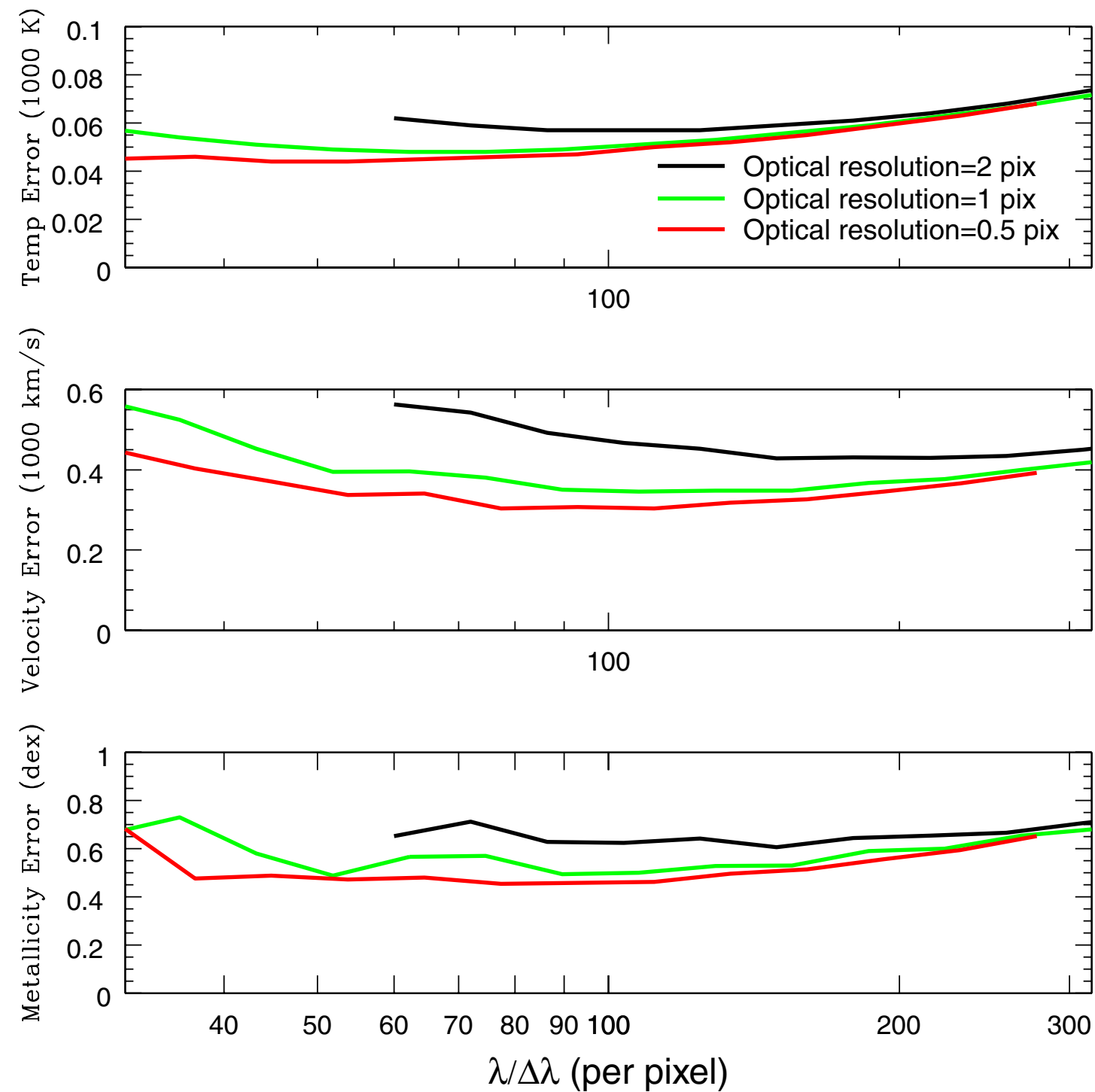
Derivatives of SN Spectra, from Peter Nugent Models
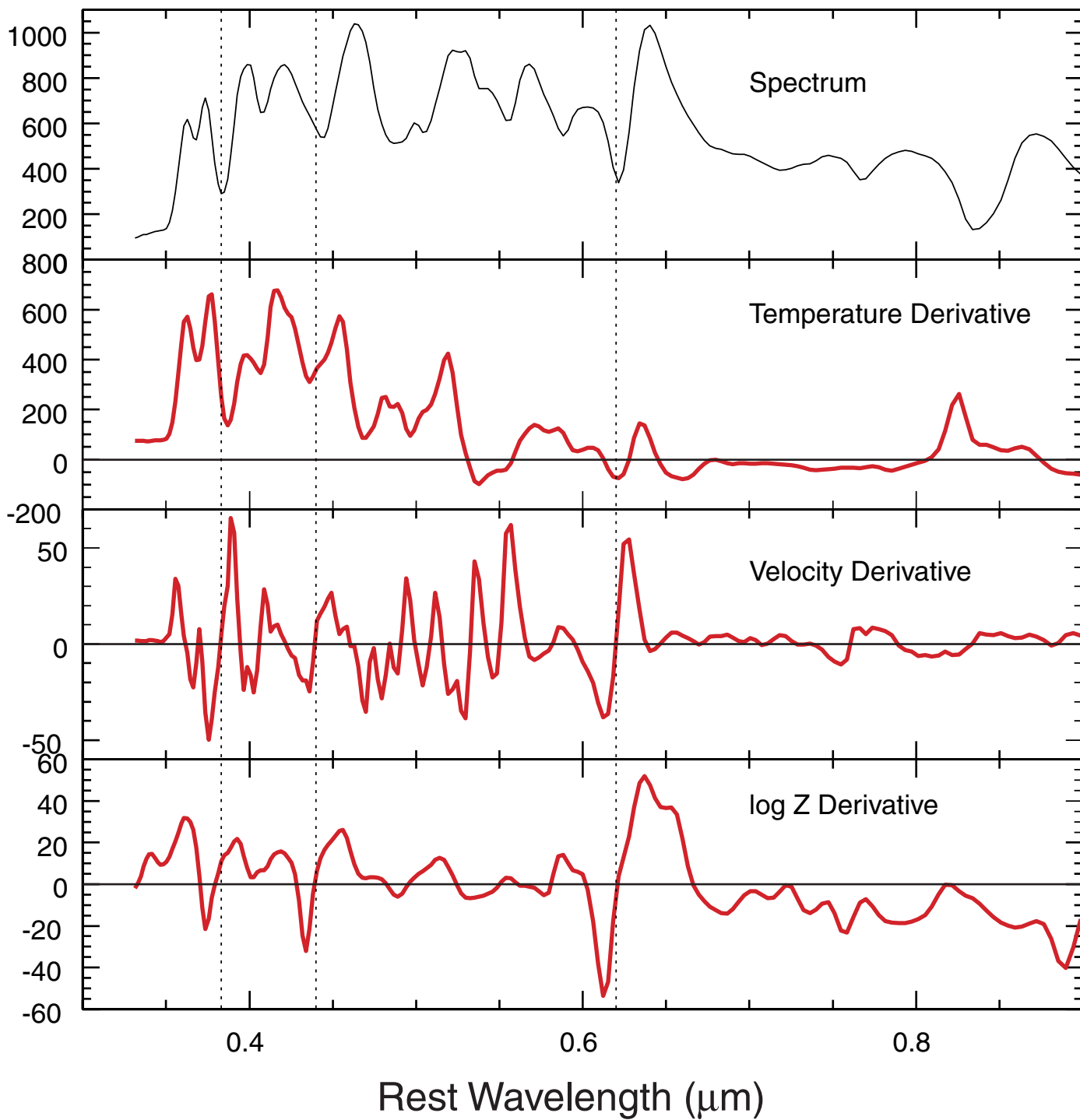
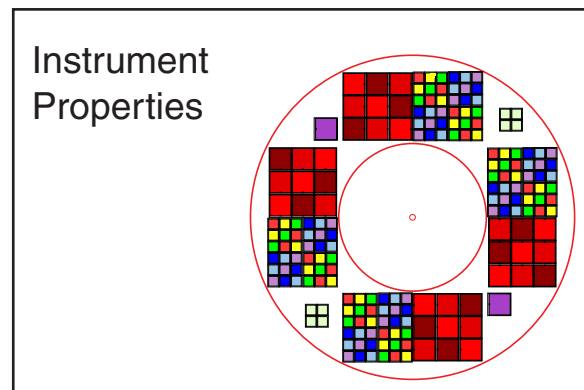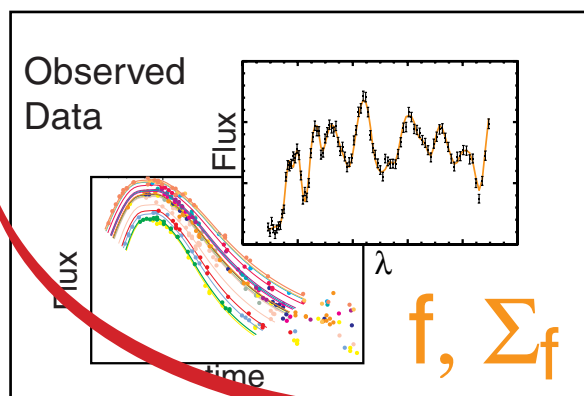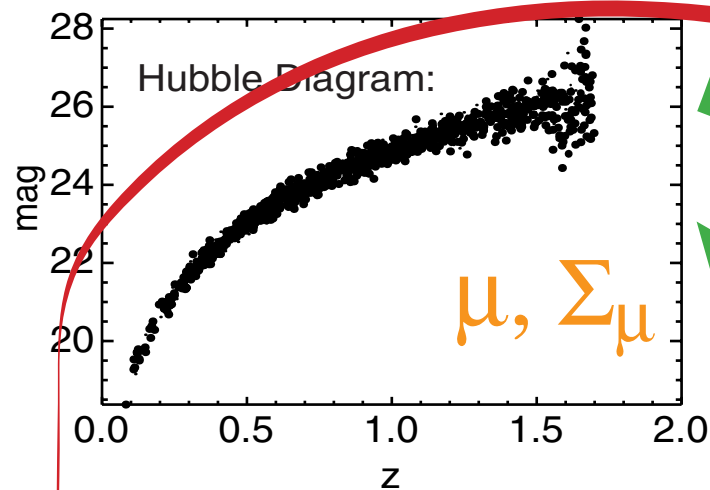# Spectroscopic Accuracy from Instrument and Mission Specifications:

- **Present Status:**
  - Software in place to calculate Fisher errors on SN parameters (T, V, Z) given instrument & mission specs.
  - Already used to optimize imager specifications.
  - Integrated into Monte-Carlo pipeline.
- **Future Work:**
  - Improved theoretical spectral templates.
  - Algorithms for spectrum extraction from image slicer data cubes.
  - Investigation into effects of residual host galaxy spectral contamination.
  - Use to analyze larger set of alternative approaches.

Spectroscopic Accuracy from Specifications: Flowdown Results

- Shot noise, zodi background, dark current, and read noise are all important for z=1.7 SNe on HgCdTe detectors.
- Substantial gains from *low-resolution* spectrograph (R~100) with 1 pixel per spectrograph FWHM. No gain from higher resolution, and "critical sampling" (2 pix per FWHM) is substantial degradation of performance.
- Two-channel (CCD + HgCdTe) spectrograph reduces time required to measure metallicity by ~40% or more.
- Time to measure SNe parameters scales as $(1+z)^6$.

Uncertainties on Supernova Parameters vs Spectrograph Resolution at Fixed Exposure Time

CASE II: z=1.7, 10-hour Integration, 7 spatial pix per spectral sample
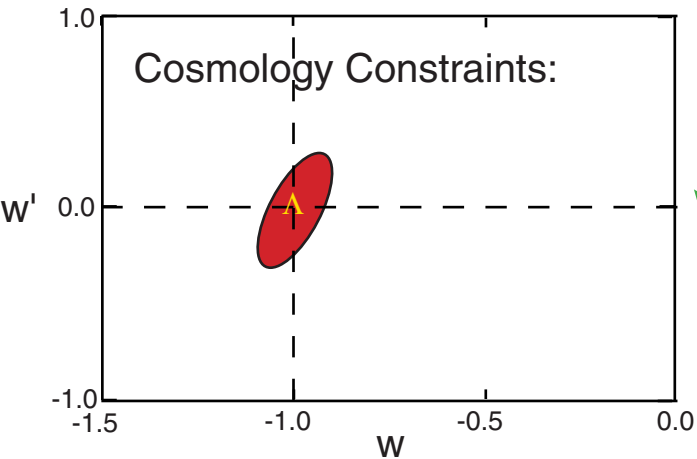
Data Flow:

Cosmology Constraints:

w'

Λ

w

Hubble Diagram:

mag

z

μ, Σ_μ

External Cosmology Prior Constraints

Σ_Ω

Observed Data

Flux

Flux

λ

Flux

time

f, Σ_f

External Supernova Observations

Σ_{sn}

Calibration Program Constraints

Σ_{cal}

Instrument Properties

Mission Plan

Requirements Flowdown

Hubble Diagram from Observed Data:

- Conversion of observed fluxes into distances requires a model of the SN events, propagation to us, and instrument calibration errors.
- Simple case:

$$m = M + \mu$$

      m is observable
      M is SN model (std candle)
      μ is propagation model

   Fit observations to the model to get best distance.

- More realistic model must include:
    - SN flux/spectrum that depends upon several physical parameters, manifested by stretch, metallicity, etc. – but not explicitly on redshift!
    - K corrections to magnitudes
    - Host dust corrections with unknown A_V, R_V
    - Possible intergalactic ("gray") dust
    - Photometric calibration uncertainties
    - Gravitational lensing magnification
    - Malmquist bias

- In previous proposal/review, each of these effects has been analyzed individually, no "killers" in the lot. But do data have enough information to constrain all simultaneously?
- The SNAP SNe analysis will be fitting a model with ~20,000 free parameters to ~200,000 or more flux observations. Tractable?
- YES – most parameters are "local" to a single event so we have techniques to hugely compress the fitting matrices. Left with best-fit values for each event's μ plus 10-20 shared "global" parameters (calibration, gray dust).
- Marginalization over global parameters gives Hubble diagram and covariance matrix.
- SN model is refined using SNAP data itself in a way that does not bias Hubble diagram:
  - Comparing similar SNe at different z to get cosmology
  - Comparing dissimilar SNe at same z to refine SN model.
 - Max-likelihood technique does both simultaneously.

Hubble Diagram from Observed Data:

- Present Status:
  - o Hoeflich & Nugent calculations used to create a representative SN model: 5+ light-curve observables and 3 spectroscopic observables depend upon 4 underlying SNe physical parameters. NOTE: theoretical models will NOT be used to derive SNAP cosmology. SN Model will be derived from SNAP and other observations, but theory tells us what effects to look for and their approximate magnitudes.
  - o Two error-propagation techniques developed: full Monte Carlo (SNAPfast – *cf*. Alex Kim presentation) and analytic max-likelihood.
  - o Basic SNAP scenario tested in Monte Carlo
- Future Work:
  - o Improved, self-consistent theoretical models for SNe over grid of physical parameters (Hoeflich).
  - o Finish programming of end-to-end simulations.
 - o Refinement of models as more SNe are observed.

Results of the End-to-End Simulation:

- Nominal SNAP mission analysis in progress – first Hubble diagrams and cosmology constraints now complete.
- Optimization of the SNAP mission plan, especially
  - spectroscopy target redshift distribution,
  - spectroscopic exposure times,
  - sub-sampling of high-z events by host type?
  - is nominal mission duration sufficient for science goal?
 - refinement of calibration requirements.

To Be Continued
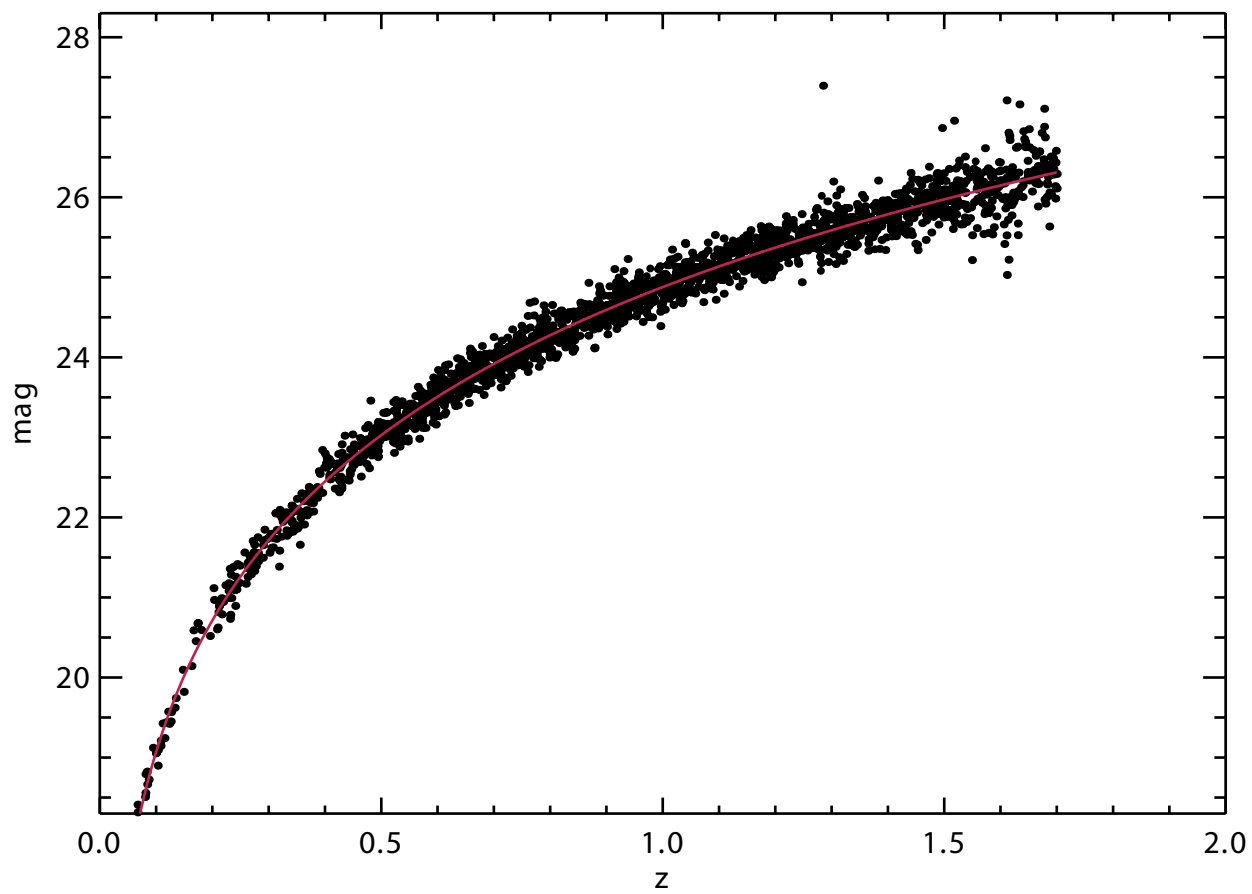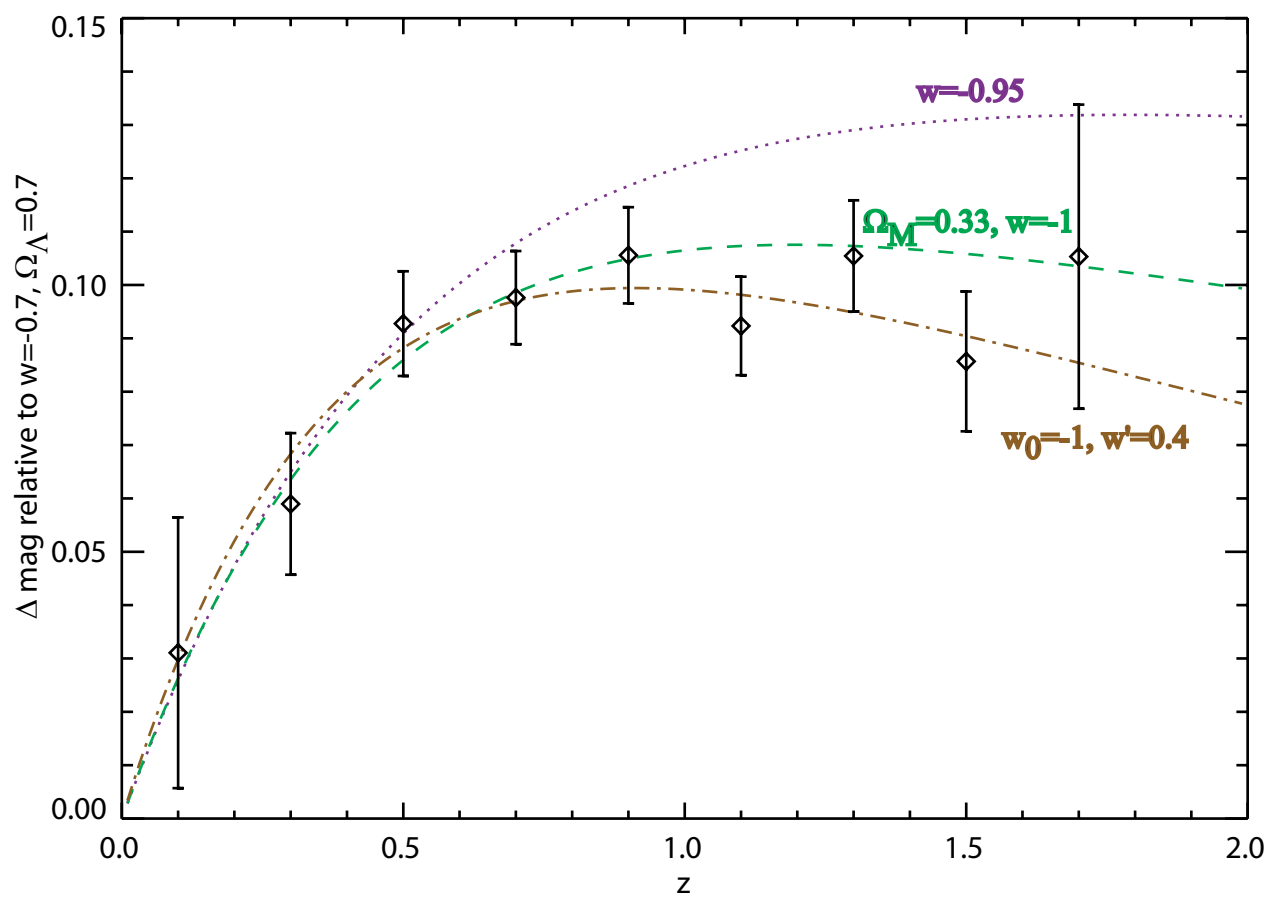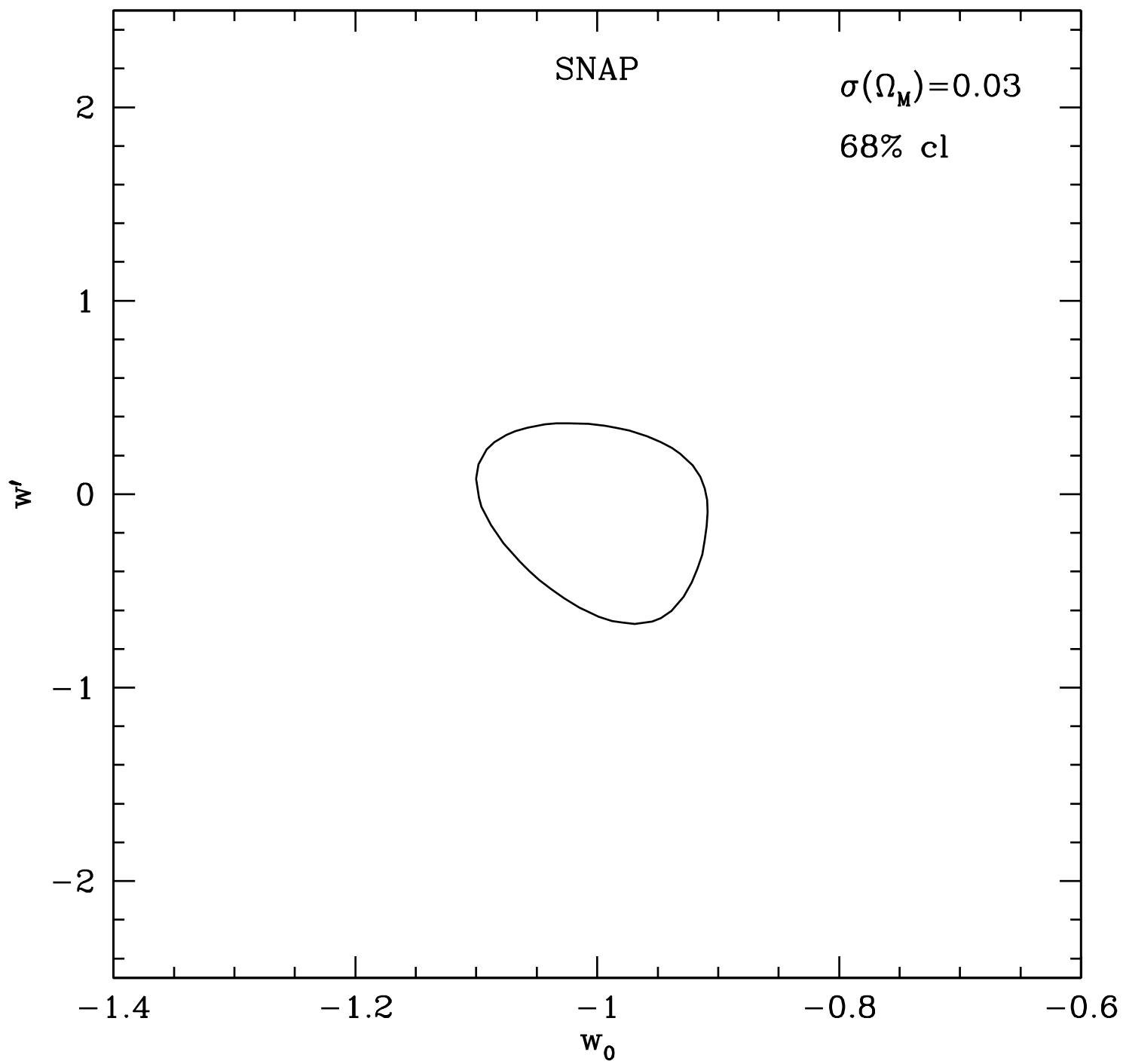
Results of the End-to-End Simulation:
Ground-Based and Other Alternatives

- All SNAP simulation tools are equipped to examine ground-based and space-based alternative sources of data.
- A best-case alternative for 2010:
  - Event detection with LSST (6.5 m, 7 deg^2) to 0.9 micron wavelength, natural seeing (POI-type alternative?)
  - Followup NIR photometry with OH-suppressed 10-meter telescope, tip-tilt correction.
  - Followup NIR spectroscopy with OH-suppressed laser-guided AO 10-meter telescope.
  - Full time on each telescope, Las Campanas weather and seeing histories.
  - Possible NGST access for NIR followup?
  - see analysis by A. Kim; still difficult to obtain sufficient photometry beyond z~0.9.
  - Ground is attractive for supplementing SNAP at z<0.8.
- End-to-end analyses of alternative scenarios continues. What z range is it productive to supplement with ground observations?
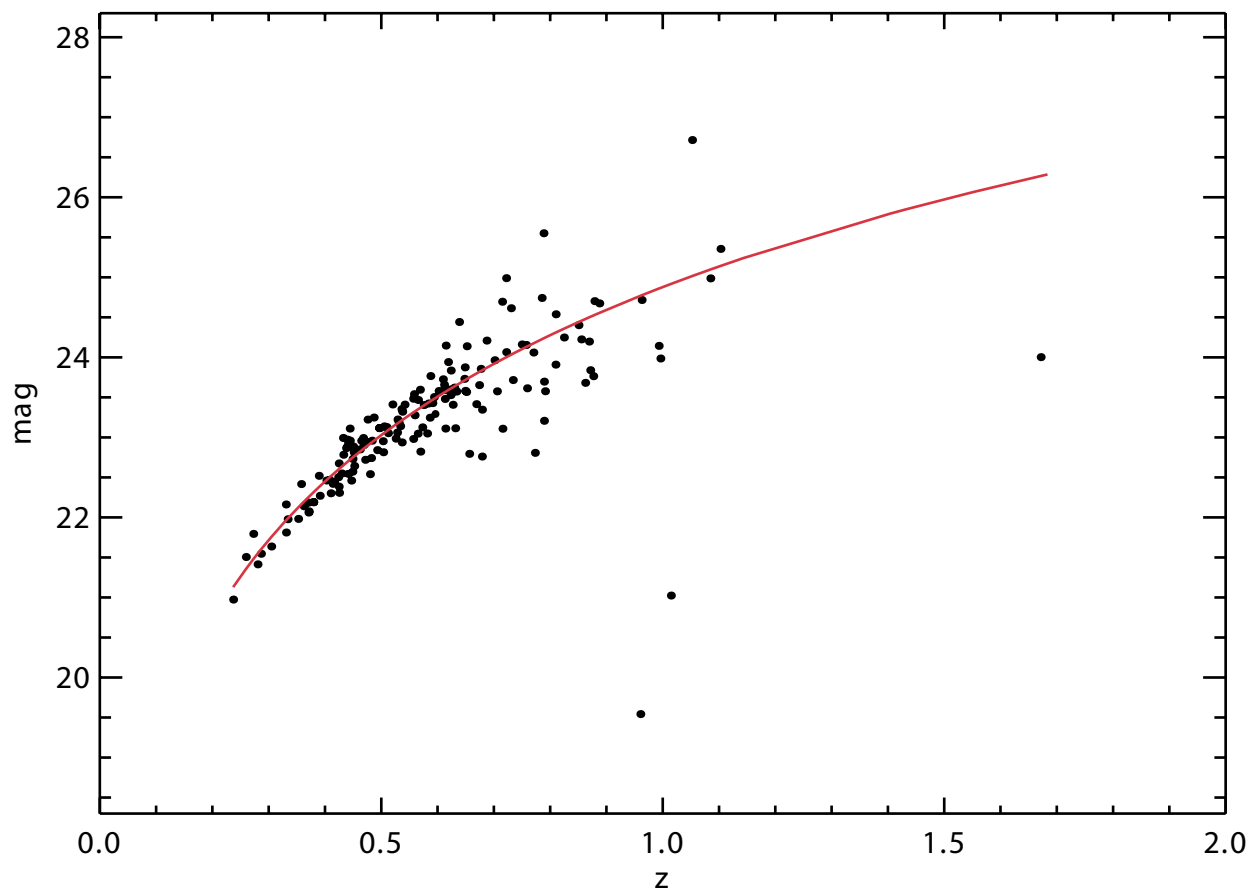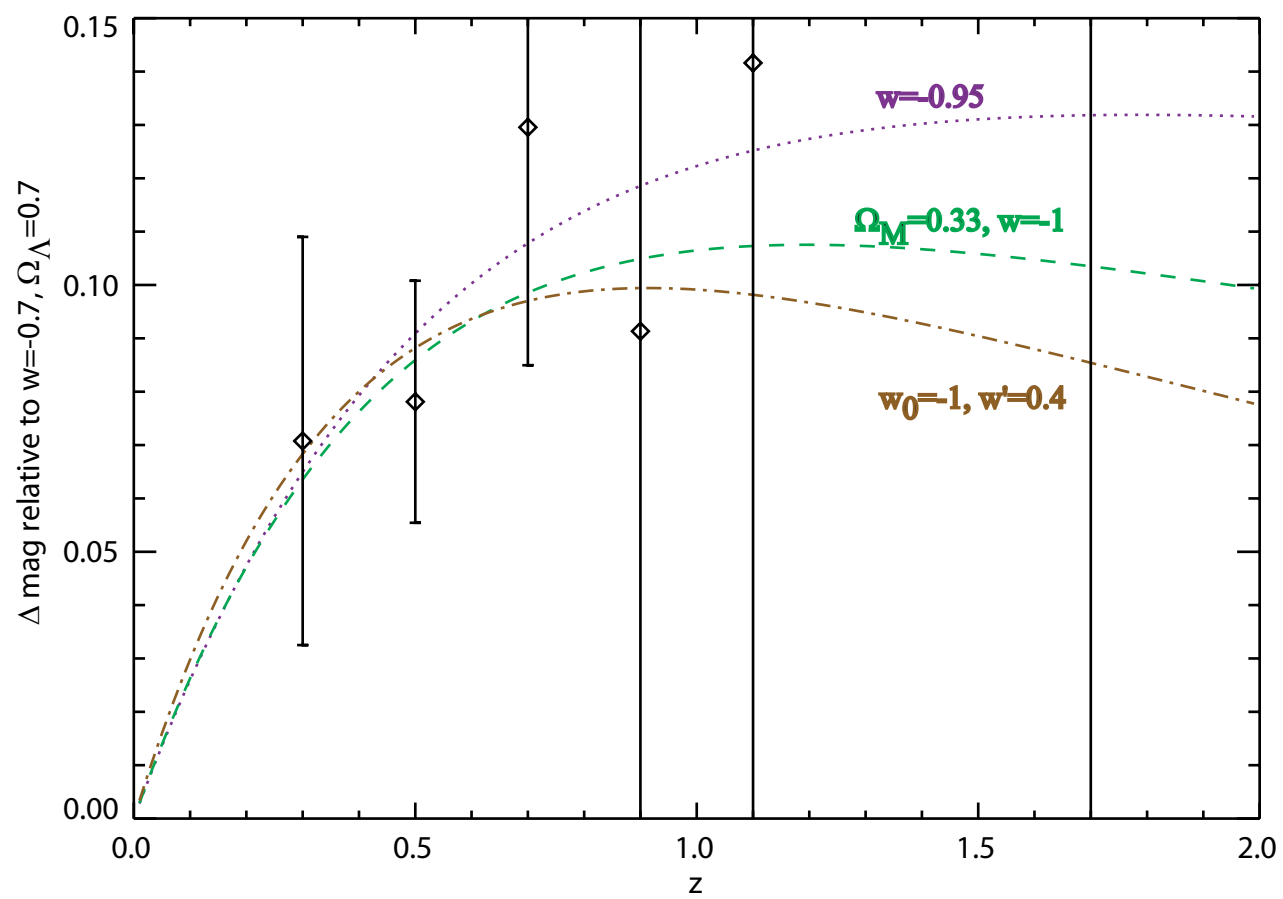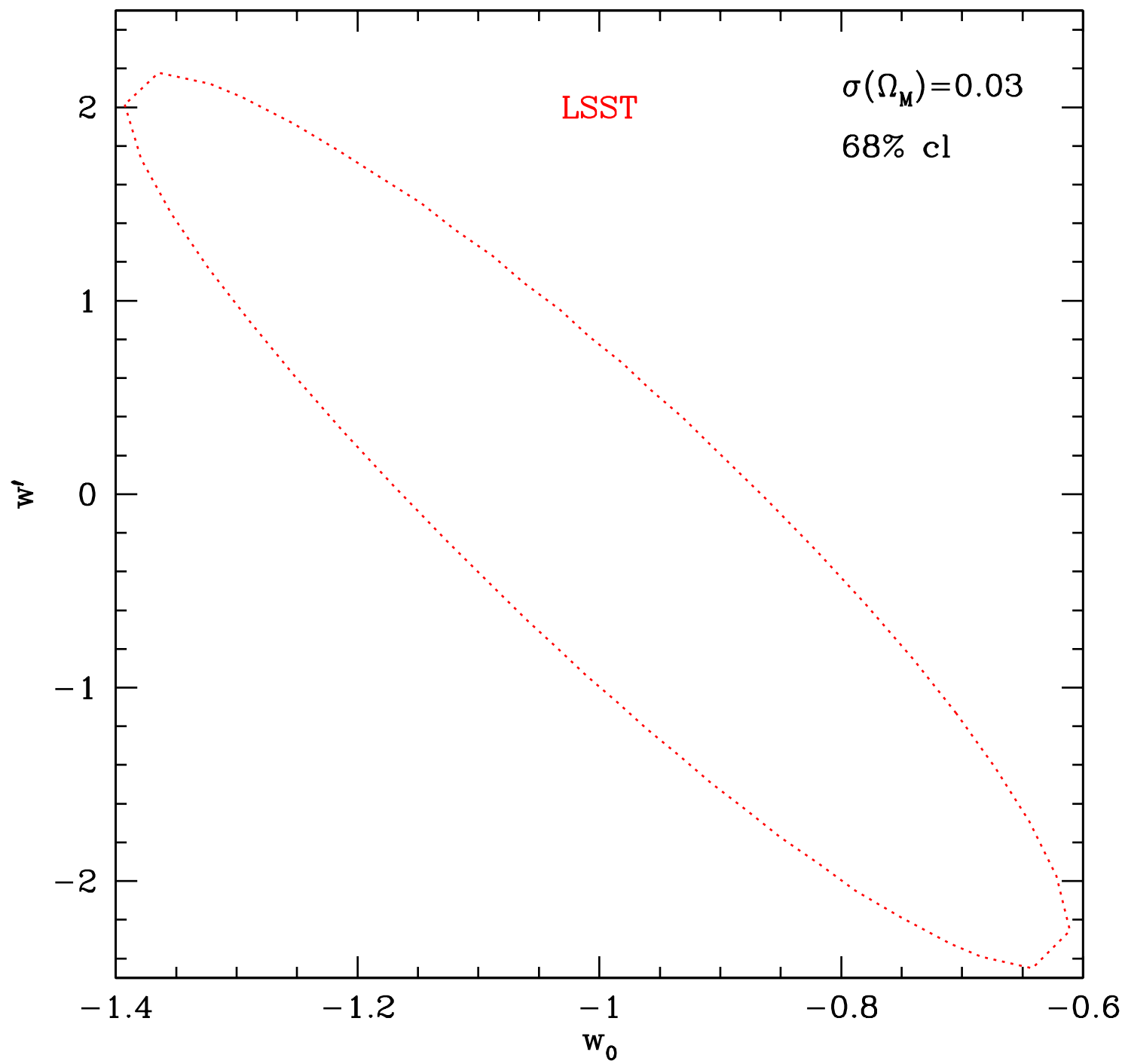
Weak Lensing with SNAP:

- Parallel data flow from instrumentation/mission specs to cosmological constraints. Instead of Hubble diagram we have lensing shear power spectra. Lensing measurement requires no sophisticated source model, just gravitational physics.
- Capability of SNAP to measure shapes of galaxies is estimated with same software package that does photometric S/N: SNAP imager is nearly ideal instrument for weak lensing! PSF more stable than any existing or planned observatory.
- Methodologies for converting shear power spectra into cosmological constraints are understood by theorists.
- Detailed calculation of SNAP lensing cosmological constraints depends upon knowing the redshift/size/mag distribution of source galaxies. Photometric redshifts will be required. Complete error estimation requires further work on:
    - o Accuracy of photo-z estimates from 9-band Vis/NIR SNAP data (should be best available in 2010)
    - o Modelling of evolution of galaxy population to estimate number of SNAP galaxies vs z
    - o Growth of structure in Universes with variable w has not been calculated yet.
    - o Analysis of non-Gaussian information is in its infancy.